To: Vought-Sikorsky Aircraft Division
United Aircraft Corp
Att: Mr C. J. McCarthy
Gen. Mgr

ACR- July 1942
# 225



[redacted]

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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# PRELIMINARY WIND-TUNNEL TESTS OF THE EFFECT OF NACELLES ON THE CHARACTERISTICS OF A TWIN-ENGINE BOMBER MODEL WITH LOW-DRAG WING

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# PRELIMINARY WIND-TUNNEL TESTS OF THE EFFECT OF NACELLES ON THE CHARACTERISTICS OF A TWIN-ENGINE BOMBER MODEL WITH LOW-DRAG WING

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## SUMMARY

Tests were made in the NACA 19-foot pressure tunnel of a simplified twin-engine bomber model with an NACA low-drag wing primarily to obtain an indication of the effects of engine nacelles on the characteristics of the model both with and without simple split trailing-edge flaps. Nacelles with conventional-type cowlings representative of those used on an existing high-performance airplane and with NACA high-speed type E cowlings were tested. The tests were made without propeller slipstream.

The aerodynamic effects of adding the nacelles to the low-drag wing were similar to the effects commonly obtained by adding similar nacelles to conventional wings. The maximum lift coefficient without flaps was slightly increased, but the increment in maximum lift due to deflecting the flaps was somewhat decreased. The stalling characteristics were improved by the presence of the nacelles. Addition of the nacelles had a destabilizing effect on the pitching moments, as is usual for nacelles that project forward of the wing. The drag increments due to the nacelles were of the usual order of magnitude, with the increment due to the nacelles with NACA type E cowlings approximately one-third less than that of the nacelles with conventional cowlings with built-in air scoops.

## INTRODUCTION

Considerable application of the NACA low-drag airfoil sections is being made to the design of military airplanes to improve their performance. A large amount of research

has already been carried out on numerous families of airfoil sections and on individual models in the NACA two-dimensional low-turbulence tunnels; this research provides data on airfoil section characteristics over a wide range of Reynolds number.

Complete airplane and wing models are currently being investigated in the NACA 19-foot pressure tunnel to obtain aerodynamic data applicable to the airplanes making use of the low-drag wing sections. Models of practically all new military airplanes are being tested, principally to determine the effects of fuselage and nacelle interference, propeller slipstream, gun installations, wing plan form and section, and stability and control characteristics including maximum lift and stalling.

Data of general interest have already been released covering wind-tunnel tests of some factors affecting the performance of a high-speed pursuit airplane with a low-drag wing. (See reference 1.) Other tests covering the effects of various types of flap on rectangular and tapered wings with low-drag airfoil sections are reported in references 2 and 3. High-speed wind-tunnel tests of several types of radial-engine nacelle on a low-drag wing section 20.7 percent thick at the nacelles are reported in reference 4. When the 19-foot pressure tunnel is not engaged in tests of specific models, it is intended to continue the research investigations of other models with low-drag wings to provide information of general interest, particularly on high-lift and lateral-control devices and on aerodynamic interferences.

The tests described in the present report were made to obtain some preliminary data relative to the effects of engine nacelles on the aerodynamic characteristics of a twin-engine bomber model. A simplified model consisting of a tapered wing with low-drag airfoil sections and a fuselage was used. Two types of engine nacelle were investigated: one with a conventional open-nose cowling representative of the type used on an existing high-performance airplane and the other with essentially the same afterbody but with an NACA high-speed cowling E. (See reference 4.) Partial-span and full-span simple split flaps were included in the tests to check their effects with and without nacelles in place on the wing.

The tests were made in the NACA 19-foot pressure tunnel with the air compressed to 35 pounds per square inch

in order to increase the obtainable Reynolds number, particularly for application to the landing condition.

## MODEL AND APPARATUS

The simplified model was built to represent a 1/6-scale proposed twin-engine bomber and consisted of wing, fuselage, and two types of nacelle. The wing had NACA low-drag airfoil sections with plan form as shown in figure 1. The sections varied from the NACA 64,2-418, a = 0.4, at the root to the NACA 66,2X-415, a = 0.6, at the tip. The wing was 17.5 percent thick at the center line of the nacelles. Aerodynamic washout, $1.35^{\circ}$, from root to tip was given to the wing to improve stalling characteristics. The fuselage was patterned after that of an existing high-performance airplane.

The first nacelles tested had conventional-type open-nose cowlings, also patterned after those of an existing high-performance airplane. Each of these cowlings had two small scoops (tested without air flow) on top of the cowling for the carburetor and a larger scoop at the bottom for the oil cooler. The other nacelles tested had the same afterbody (without the oil-cooler duct) but had NACA type E cowlings (reference 4). The rotatable nose of the cowling was so fixed that it could not rotate and the blower blades were placed in line with the air flow through the cowlings. The air flow through both types of nacelle was adjusted to approximate as closely as possible the cooling-air requirements of the P. & W. 2800-series engines used in the existing high-performance airplane from which the fuselage and the conventional-type nacelles were patterned. Perforated baffle plates were used to simulate the engine resistance and to give the desired pressure drop. Both types of nacelle are shown in figure 2. No details of the full-scale airplane other than those described were included on the model for the present tests.

The wing, the fuselage, and the nacelles were all constructed of laminated mahogany to the dimensions shown in figures 1 and 2. All surfaces of the model were given a finish classified as aerodynamically smooth by spraying with several coats of lacquer and rubbing with No. 400 carborundum paper. The nacelles were made removable in order that tests could be made with and without them.

Simple split flaps, both partial-span and full-span, were made of 1/16-inch steel sheet and were attached to the model by wood blocks and screws for the deflection desired. When the nacelles were not in place, the partial-span flaps extended completely across the portion of the span that would be occupied by the nacelles. When the nacelles were in place, the partial-span flaps were cut to allow for the nacelles and the cut edges were bent to represent the fillets between the nacelles and the wing. These cut-outs in the flaps for the nacelles permitted a certain amount of air leakage between nacelle and flap. In order to determine the effect of this air leakage, partial-span flaps were also made with sections cut to fit closely around the nacelles with NACA type E cowlings and any gap left was sealed to prevent air leakage. Photographs of the model without nacelles, with both types of nacelle, without flaps, and with both types of flap are reproduced as figures 3 to 7.

The model mounted on the standard supports for tests in the 19-foot pressure tunnel is shown in figure 3. The angle of attack covered a range from below zero lift to beyond maximum lift for most of the tests. The angle of attack was measured with respect to the thrust line of the nacelles. The root chord of the wing was set at an angle of incidence of $1^{\circ}$ with respect to the thrust line. Because of strength limitations of the model for the maximum-lift condition, the highest dynamic pressure for the tests for maximum lift was about 70 pounds per square foot, which gave a test Reynolds number of approximately 3,700,000. Tests were made for lift coefficients up to 1.1 at a dynamic pressure of 150 pounds per square foot, giving a test Reynolds number of approximately 5,400,000.

Force tests were made for the following arrangements of the model:

Fuselage + wing (fig. 3)

Fuselage + wing + two nacelles with conventional cowlings (fig. 4)

Fuselage + wing + partial-span flaps

Fuselage + wing + partial-span flaps + two nacelles with conventional cowlings (fig. 5)

Fuselage + wing + full-span flap + two nacelles with conventional cowlings

Fuselage + wing + two nacelles with NACA type E cowlings (fig. 6)

Fuselage + wing + partial-span flaps cut at nacelles + two nacelles with NACA type E cowlings

Fuselage + wing + partial-span flaps sealed around nacelles + two nacelles with NACA type E cowlings (fig. 7)

Measurements were made of lift, drag, and pitching moment. The stalling characteristics were obtained by observing the action of wool tufts attached to the upper surface of the wing for the various model configurations.

## RESULTS AND DISCUSSION

### Coefficients and Symbols

The results are presented as absolute coefficients, corrected for the tares and interference due to the model supports and for tunnel-wall effects. The coefficients and symbols are defined as follows:

$C_L$ lift coefficient $(L/qS)$

$C_D$ drag coefficient $(D/qS)$

$\Delta C_D$ increment of nacelle-drag coefficient of two nacelles based on wing area $\left[(C_D \text{ with nacelles}) - (C_D \text{ without nacelles})\right]$

$C_{D_F}$ effective nacelle-drag coefficient of nacelles based on frontal area of two nacelles $(\Delta D/qF)$

$C_m$ pitching-moment coefficient about center of gravity $(M/qSc)$

where

L lift

D drag

$\Delta D$ increment of nacelle drag of two nacelles $\left[(D \text{ with nacelles}) - (D \text{ without nacelles})\right]$

$M$ pitching moment about center of gravity

$q$ dynamic pressure in undisturbed air stream $\left(\frac{1}{2}\rho V^2\right)$

$S$ wing area (23.58 sq ft)

$F$ frontal area of two nacelles (1.111 sq ft for nacelles with conventional-type cowlings; 1.091 sq ft for nacelles with NACA type E cowlings)

$c$ mean wing chord (S/b = 1.626 ft)

$b$ wing span (14.5 ft)

$\rho$ mass density of air, slugs per cubic foot

$V$ velocity of undisturbed air stream

and

$\alpha$ angle of attack of thrust line corrected for tunnel-wall effect

$\delta_f$ flap deflection measured between lower surface of wing and flap

$R$ test Reynolds number based on mean wing chord $\left(\rho \frac{Vc}{\mu}\right)$

$\mu$ coefficient of viscosity

## Lift and Stalling Characteristics

The variation of lift coefficient with angle of attack is shown in figures 8 and 9. It is of interest to note that, for the model without flaps, the lift was decreased by the addition of the nacelles for the lower range of angle of attack but, beyond an angle of attack of about 14° for the nacelles with conventional cowlings (9° for the nacelles with the NACA type E cowlings), the lift was increased and a higher maximum value was obtained. This increase in maximum lift with the nacelles in the low position has been obtained with similar arrangements on

conventional wing sections. The effect may be attributed in part to the interruption by the nacelles of the cross flow on the upper surface of the wing near the trailing edge and in part to an effective increase in wing area. The lift for the model with the nacelles and NACA type E cowlings was greater throughout most of the range of angle of attack and had a higher maximum than that for the nacelles with conventional cowlings. This effect is probably due to the better nose shape and to the addition of the cowling exit slot on top of the nacelle, which helped to maintain the air flow over the nacelle. This improvement in air flow can be seen from a study of the stall diagrams (figs. 10 to 15).

The increment in maximum lift coefficient due to adding partial-span flaps (cut at the nacelles) deflected 55° was 0.59 for the model without nacelles, 0.45 for the model with nacelles with conventional cowlings, and 0.48 for the model with nacelles with NACA type E cowlings. When the gaps were closed between the flaps and the nacelles with NACA type E cowlings, the increment in maximum lift coefficient due to the flaps became 0.51. These values show that the effectiveness of the flaps were reduced by the presence of the nacelles as would be expected. The values of maximum lift coefficients obtained are given in the following table:

| Type of cowling | Type of flap | $C_{L_{max}}$ |
|---|---|---|
| No nacelle | No flap | 1.38 |
| Conventional | ---do.------- | 1.42 |
| Type E | ---do.------- | 1.47 |
| No nacelle | Partial-span | 1.97 |
| Conventional | Partial-span cut at nacelle | 1.87 |
| Type E | Partial-span cut at nacelle | 1.95 |
| Do.------- | Partial-span fitted to nacelle | 1.98 |
| Conventional | Full-span cut at nacelle | 2.11 |

It is seen that, for the nacelles with the NACA type E cowlings, the added lift due to the increase in projected area balanced the decrease in effectiveness of the flaps. As a result, the maximum lift coefficient was approximately the same as for the model without nacelles but with continuous flaps. No tests were made without nacelles and with full-span flaps. With nacelles with conventional cowlings, however, a maximum lift coefficient of about 2.11 was obtained with full-span flaps, giving an increment of 0.69 from the flap-neutral condition.

The stalling characteristics of the model with low-drag wing with and without flaps and with and without both types of nacelle are shown on the stall diagrams (figs. 10 to 15). Several interesting observations may be made on the manner in which the wing stalls for the various arrangements. The deflection of the flaps made little difference in the manner in which the wing stalled but did change the angle at which the stall occurred. Closing the gap between the flaps and the nacelles made practically no difference in the stall. The absence or presence of the nacelles and the type of cowling made an appreciable difference in the stalling characteristics.

Without the nacelles in place, the stall started at the trailing edge of the wing about halfway between the fuselage and the tip of the wing and progressed forward more toward the fuselage than toward the tip. The tip was the last place to stall.

With the nacelles with conventional cowlings in place, the stall started at a low angle of attack (about $5^{\circ}$) at the trailing edge between the nacelles and the fuselage. At a slightly higher angle of attack, stalling started outboard of the nacelles at the trailing edge. The stall progressed forward and spread out, leaving the portions of the wing on the center lines of the nacelles unstalled until a relatively high angle of attack was reached. The cross flow of air near the trailing edge of the wing was interrupted by the nacelles, an effect that may be a contributing factor toward the higher maximum lift obtained with nacelles than without them.

With the nacelles with NACA type E cowlings in place, the stall started at a higher angle than for nacelles with conventional cowlings, although the air flow was rough near the trailing edge at and inboard of the center lines of the nacelles. This rough air flow was probably due to

the addition of the exit slots at the top of the nacelles. The stall started just outboard of the nacelles and spread forward both inwardly and outwardly. The portion of the wing between the fuselage and the nacelles was extremely late in stalling. In all cases the tips of the wing were late in stalling, thus showing the effect of the aerodynamic washout. The higher lift and smoother stalling obtained with these nacelles was probably due to the better shape of the cowling and to the additional exit slots. Allowing some of the cooling air to flow over the top of the wing seemed to help control the air flow over the wing and to delay somewhat the stall at this part of the wing.

## Pitching-Moment Characteristics

From the pitching-moment-coefficient curves (figs. 16 and 17) it is evident that the effect of the addition of nacelles both with flaps neutral and with flaps deflected was to decrease the slope of the curves so that the model was less stable than it was without the nacelles. This decrease in stability is characteristic of forward-projecting nacelles and is also obtained with similar arrangements on conventional wing sections. The type of cowling used made little difference in the slope of the pitching-moment curves. In the case of the model with partial-span flaps deflected, the effect on the pitching-moment curves due to sealing the gaps between the flaps and the nacelles was practically negligible.

## Drag Characteristics

The drag-coefficient curves (figs. 16 and 17) for the condition with the partial-span flaps deflected show the effect of cutting away part of the flaps to allow for the nacelles. The drag was less with the nacelles in place and with leakage between the nacelles and the flaps than with the nacelles removed and the flaps continuous. By fitting the flaps around the nacelles and thus stopping the leakage, the drag was increased somewhat but was still less than that with the nacelles removed and the flaps continuous. The drag of the model with nacelles and with the same type of flap was practically identical for both types of nacelle.

For the condition with flaps neutral, the drag coefficients have been plotted against lift coefficient up to

1.1 (fig. 18) for the conditions of the model without nacelles and with each type of nacelle at the two test Reynolds numbers of 3,700,000 and 5,400,000. From these curves, the increment in drag due to the addition of the nacelles with air flow through them has been obtained and plotted as increment of nacelle-drag coefficient in figure 19.

At a Reynolds number of approximately 3,700,000 and for a lift coefficient of 0.2, the assumed high-speed condition of the airplane, the drag increment, based on wing area, of the nacelles with the conventional-type cowlings was 0.0047; whereas the drag increment for the nacelles with the NACA type E cowlings was 0.0032. Because nacelle-drag coefficients based upon the frontal area of the nacelles better indicate the relative merits of various nacelle designs, the increment in drag due to the nacelles was converted to this basis and is shown in figure 19 as $C_{D_F}$; this effective drag coefficient includes interference effects and the internal drag due to the flow of air through the nacelles. The values of the internal drag coefficient, measured in the case of the NACA type E cowlings and estimated in the case of the conventional cowlings, were of the order of 0.005 to 0.011 based on frontal area. On the basis of frontal area, the effective drag coefficients were 0.102 for the nacelles with conventional cowlings and 0.069 for the nacelles with NACA type E cowlings, an improvement of about 32 percent.

At a Reynolds number of approximately 5,400,000, the values of the drag coefficients for the two conventional nacelles were practically the same as for a Reynolds number of 3,700,000 but, for the nacelles with NACA type E cowlings, the drag coefficients became $\Delta C_D = 0.0029$ and $C_{D_F} = 0.062$, an improvement of about 39 percent. It is of interest to note that, at the higher values of lift coefficient, the drag of the conventional nacelles becomes much greater than that of the nacelles with the type E cowlings.

It should be pointed out that the conventional-type cowlings were not the best of their type and that the differences in drag of the two types of cowling tested do not indicate that there would be as much difference in drag with the best cowlings of each general type. Also, because of time limitations for use of the tunnel, no effects of propeller slipstream were included in the tests.

## CONCLUSIONS

Based on the results of the preliminary tests, the following conclusions may be drawn:

1. The aerodynamic effects of adding nacelles to the low-drag wing of a simplified twin-engine bomber model were similar to the effects commonly obtained when wings of conventional section are employed. Without flaps the lift was decreased in the low-lift region but the maximum lift was slightly increased. The nacelles had a destabilizing effect on the pitching moment as is usual for nacelles that project forward of the wing.

2. The increment in maximum lift due to deflecting the flaps was appreciably decreased by the addition of the nacelles with conventional cowlings and was slightly decreased by the addition of the nacelles with NACA type E cowlings because the low nacelle afterbody interrupted or covered over part of the flap. A lift increment, apparently associated with the increased effective wing area due to the forward-projecting nacelles, tended to balance the decrease in flap effectiveness and, as a result, the maximum lift coefficient for the nacelles with NACA type E cowlings was practically the same as that without nacelles.

3. Stalling characteristics were little affected by deflecting split flaps. With the nacelles with conventional cowlings in place, the stall started at a lower angle of attack and spread more gradually. With the nacelles with NACA type E cowlings in place, the stall was delayed somewhat and again spread gradually, leaving that portion of the wing between nacelles and fuselage along with the wing tips unstalled until late.

4. The drag increments due to the nacelles were of the usual order of magnitude; with the NACA type E cowlings the increment was approximately one-third less than that with the nacelles with conventional cowlings incorporating three built-in scoops.

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2. Muse, Thomas C., and Neely, Robert H.: Wind-Tunnel Investigation of an NACA 66,2-216 Low-Drag Wing with Split Flaps of Various Sizes. NACA A.C.R., Sept. 1941.

3. Muse, Thomas C., and Neely, Robert H.: Wind-Tunnel Investigation of an NACA Low-Drag Tapered Wing with Straight Trailing Edge and Simple Split Flaps. NACA A.C.R., Dec. 1941.

4. Becker, John V.: High-Speed Tests of Radial-Engine Nacelles on a Thick Low-Drag Wing. NACA A.C.R., May 1942.

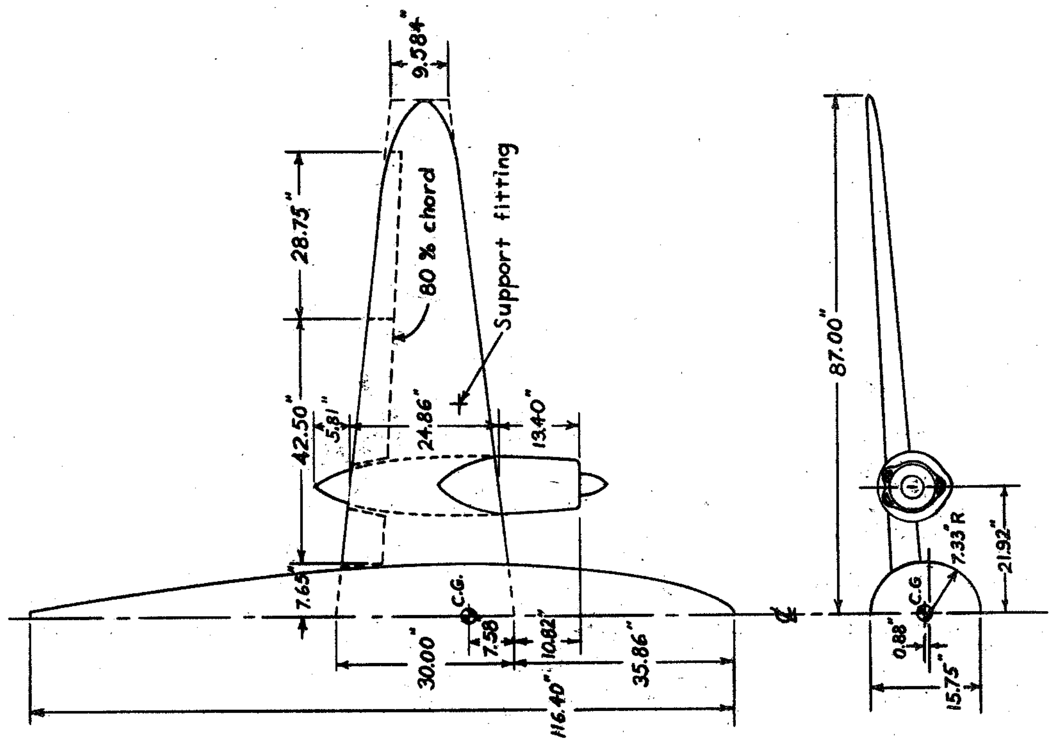


Figure 1.- Plan and elevation of the 1/6-scale simplified twin-engine bomber model with nacelles with conventional-type cowlings.

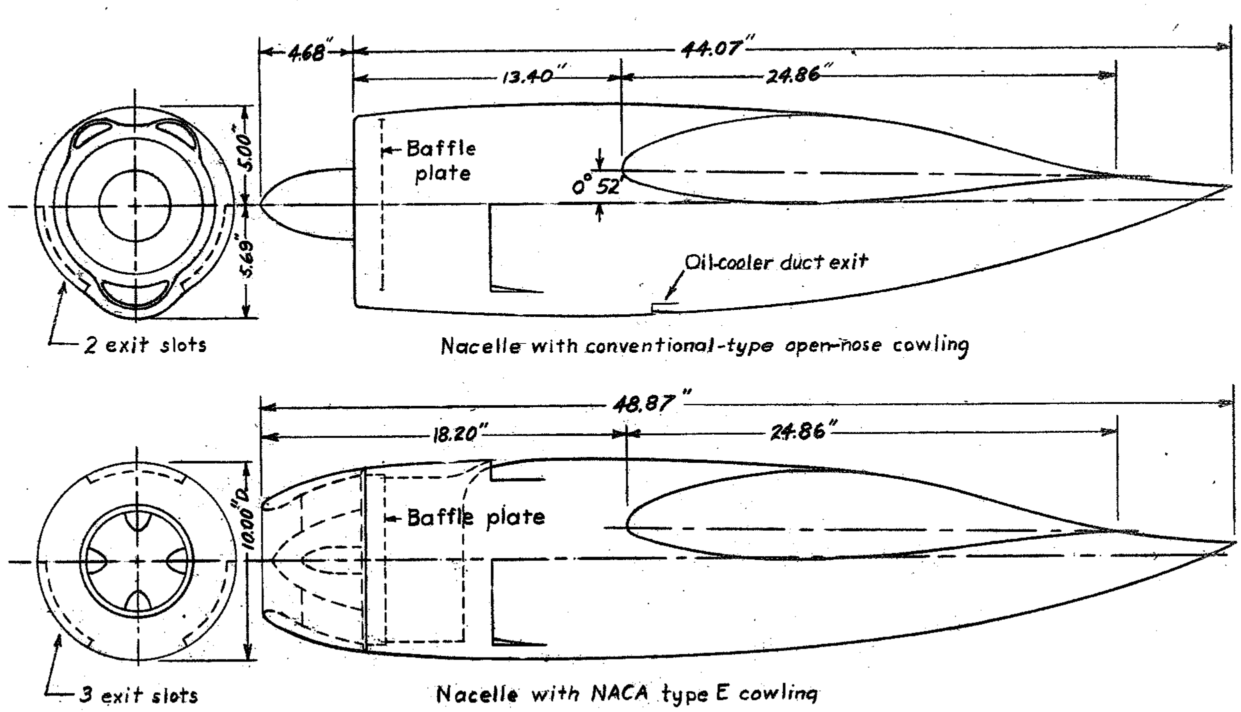


Figure 2.- Nacelles and wing section of the 1/6-scale simplified twin-engine bomber model.

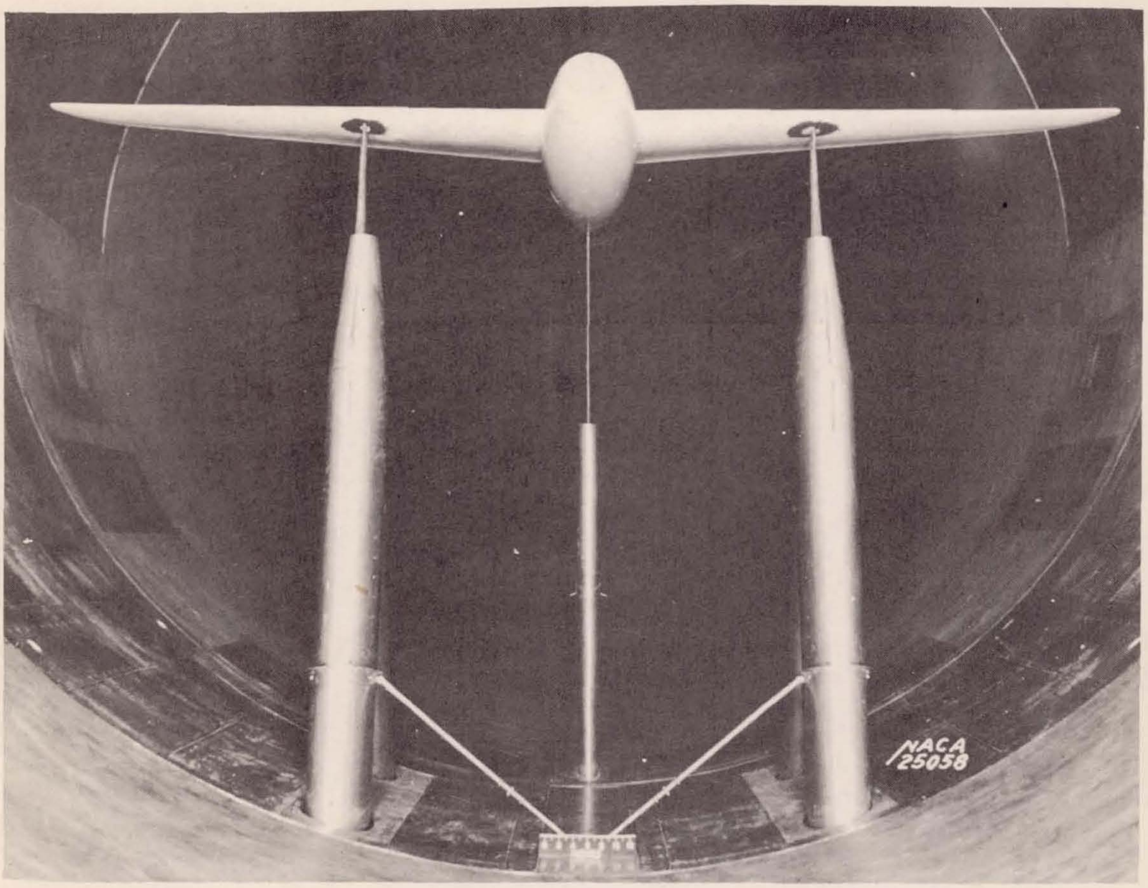


Figure 3.- The 1/6-scale simplified bomber model set-up for test in the 19-foot pressure tunnel.

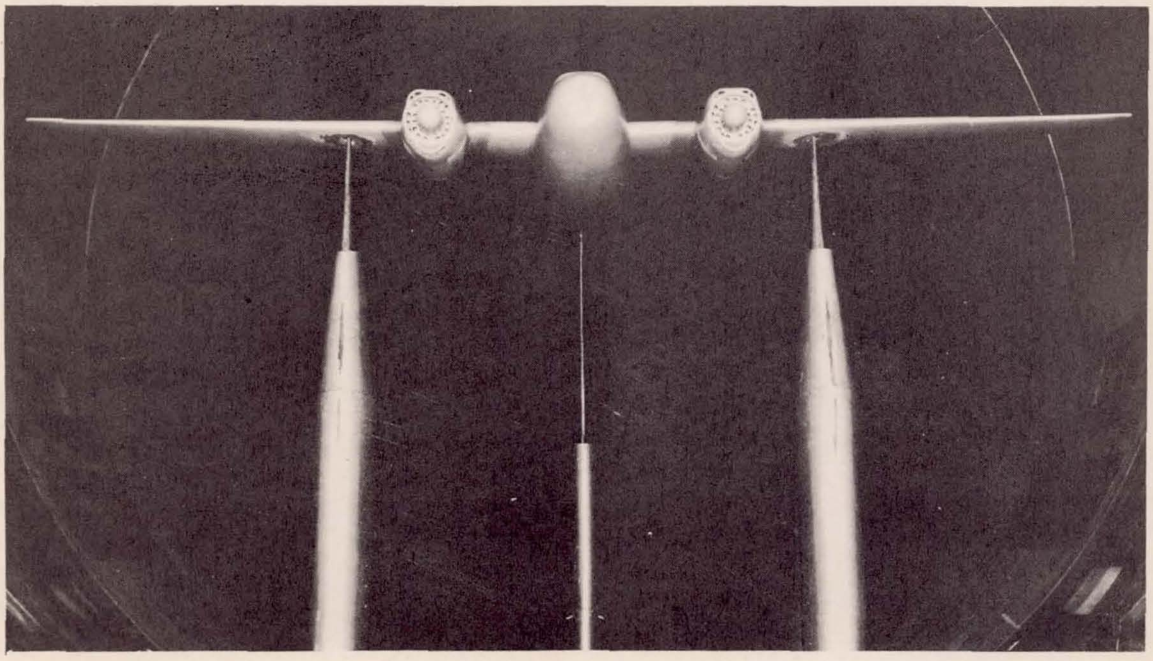

Figure 4.- Model with two nacelles with conventional-type cowlings.

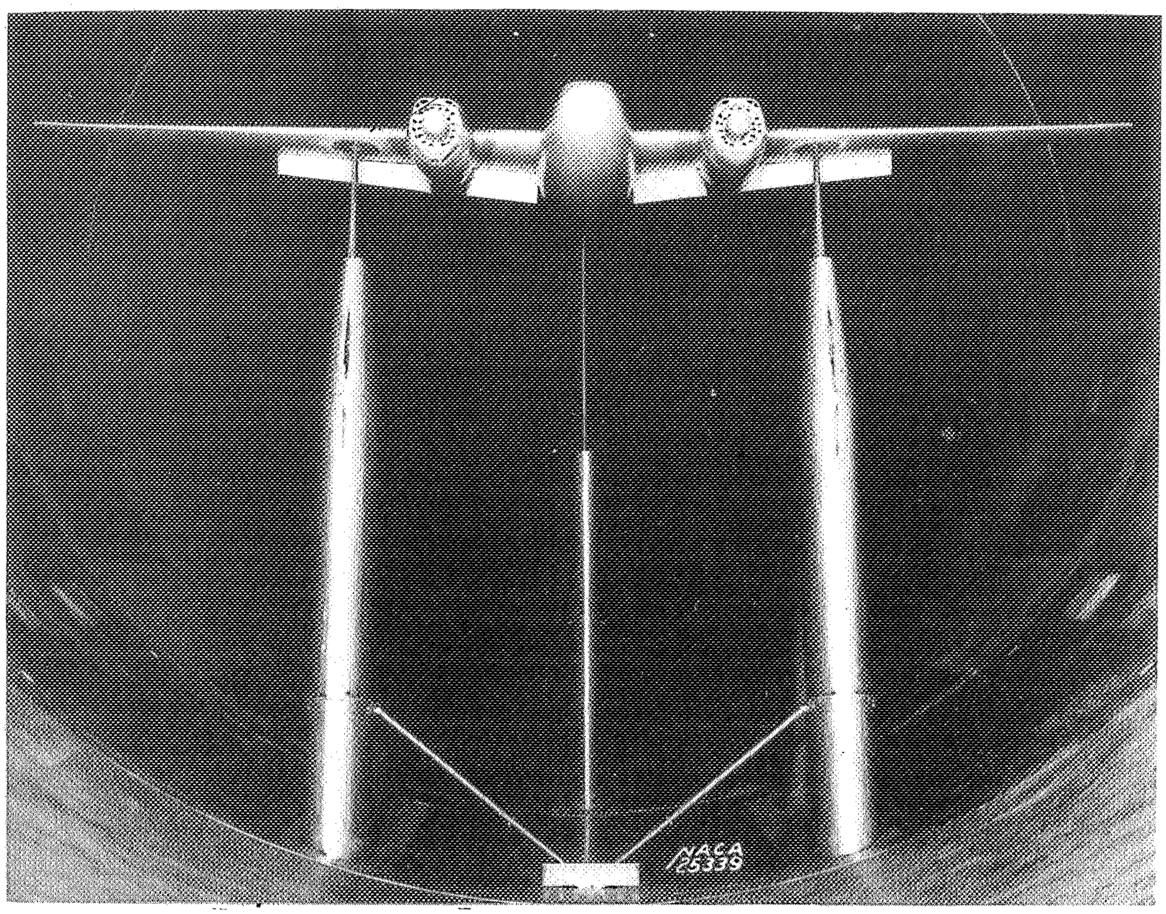


Figure 5.- Model with two nacelles with conventional-type cowlings and partial-span split flaps cut at the nacelles.

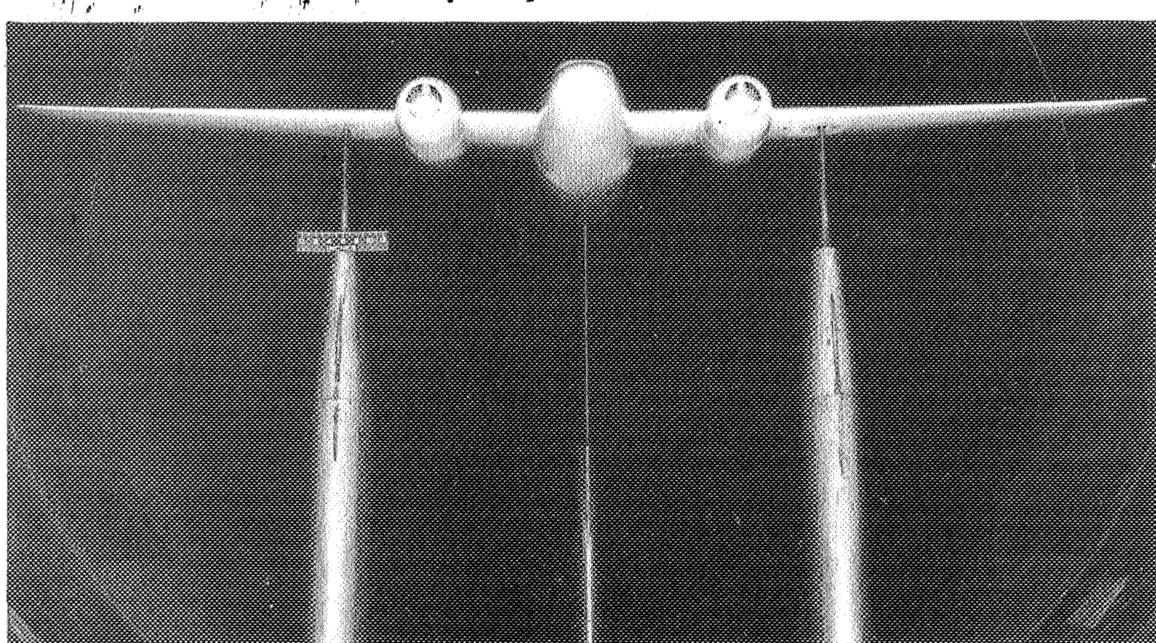

Figure 6.- Model with two nacelles with NACA type E cowlings.

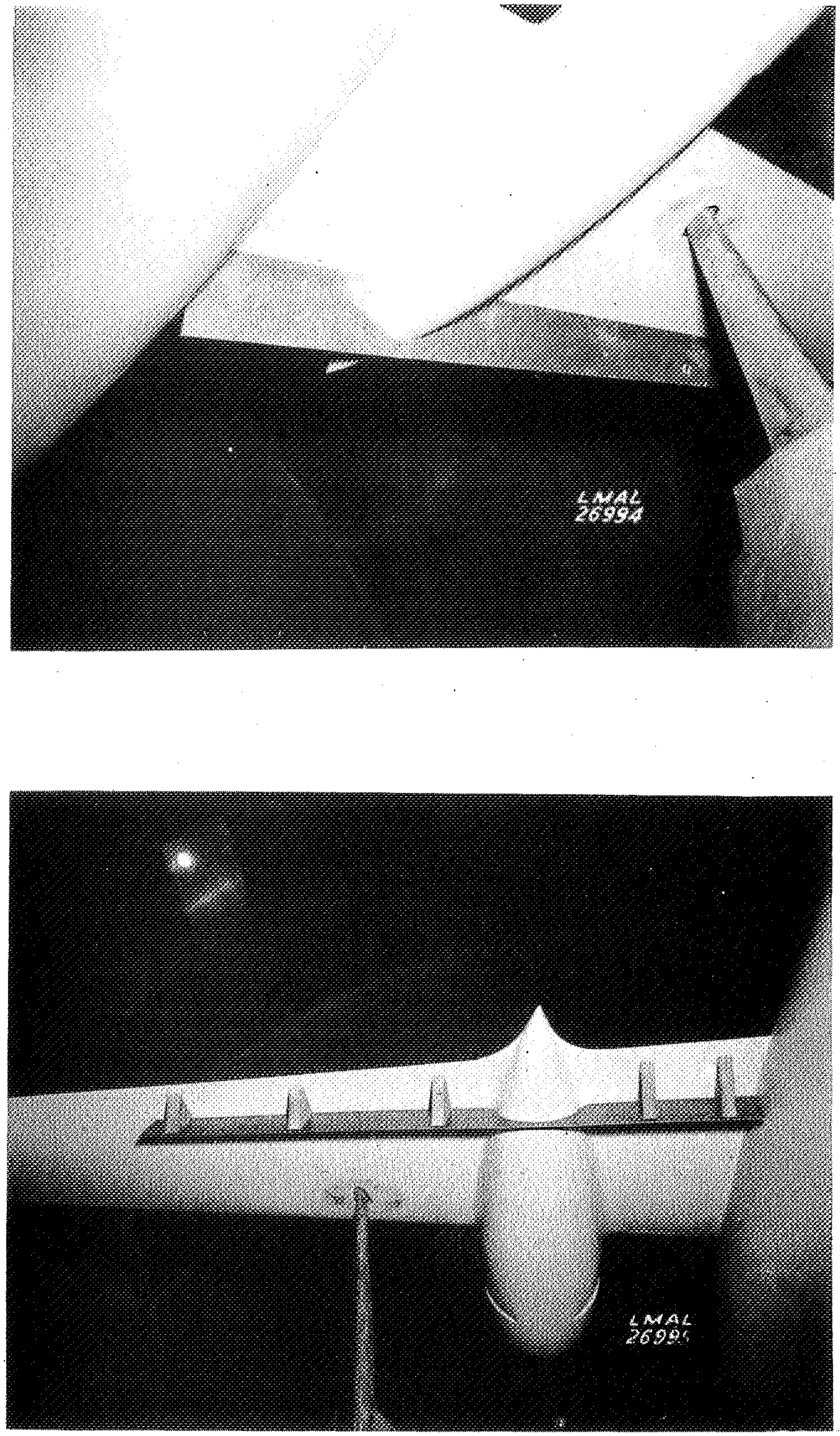


Figure 7.- Details of partial-span split flaps fitted around nacelles with NACA type E cowlings.

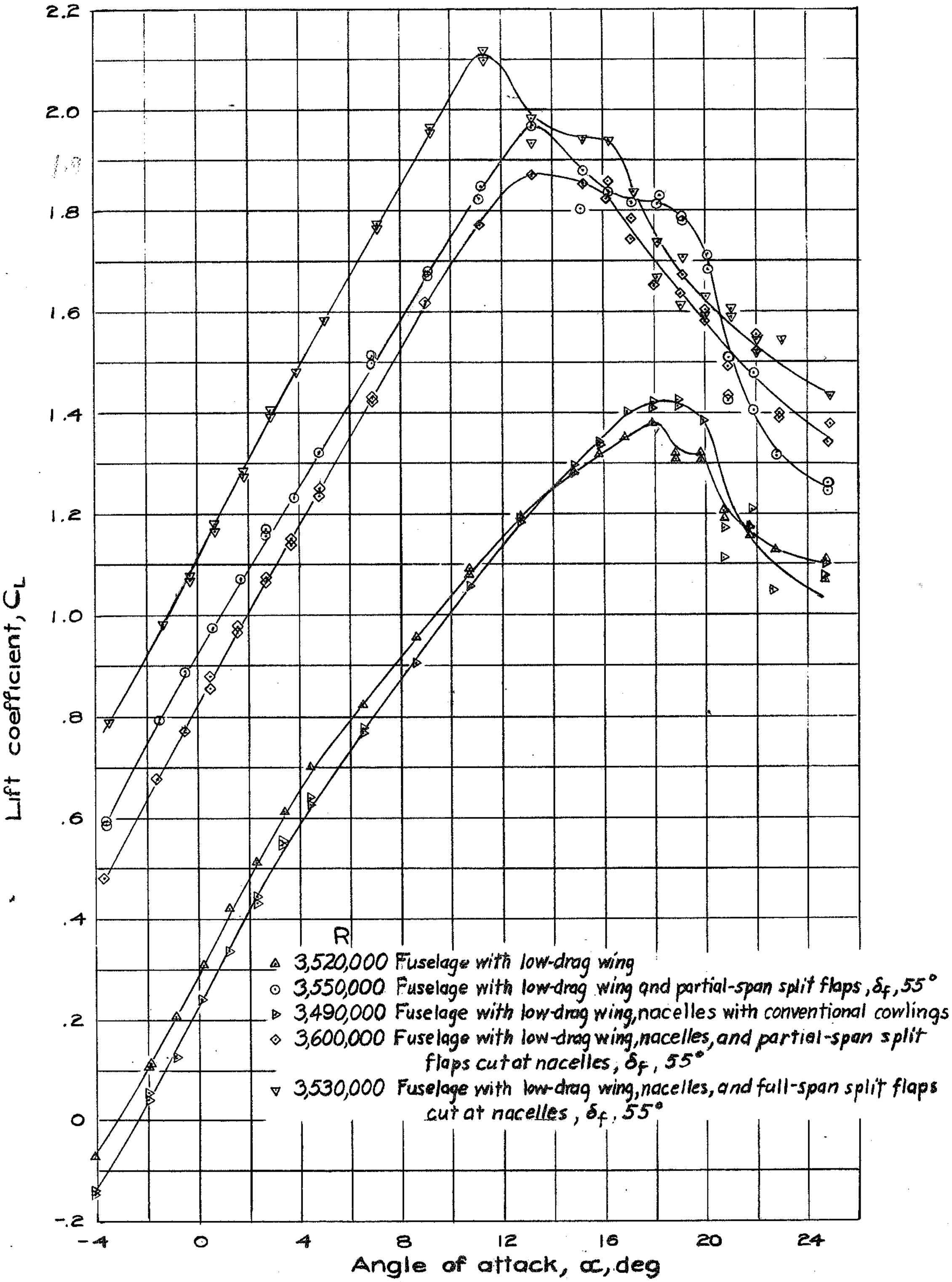


Figure 8.- Variation of lift coefficient with angle of attack for model without nacelles and with two nacelles with conventional-type cowlings. q, 30 pounds per square foot.

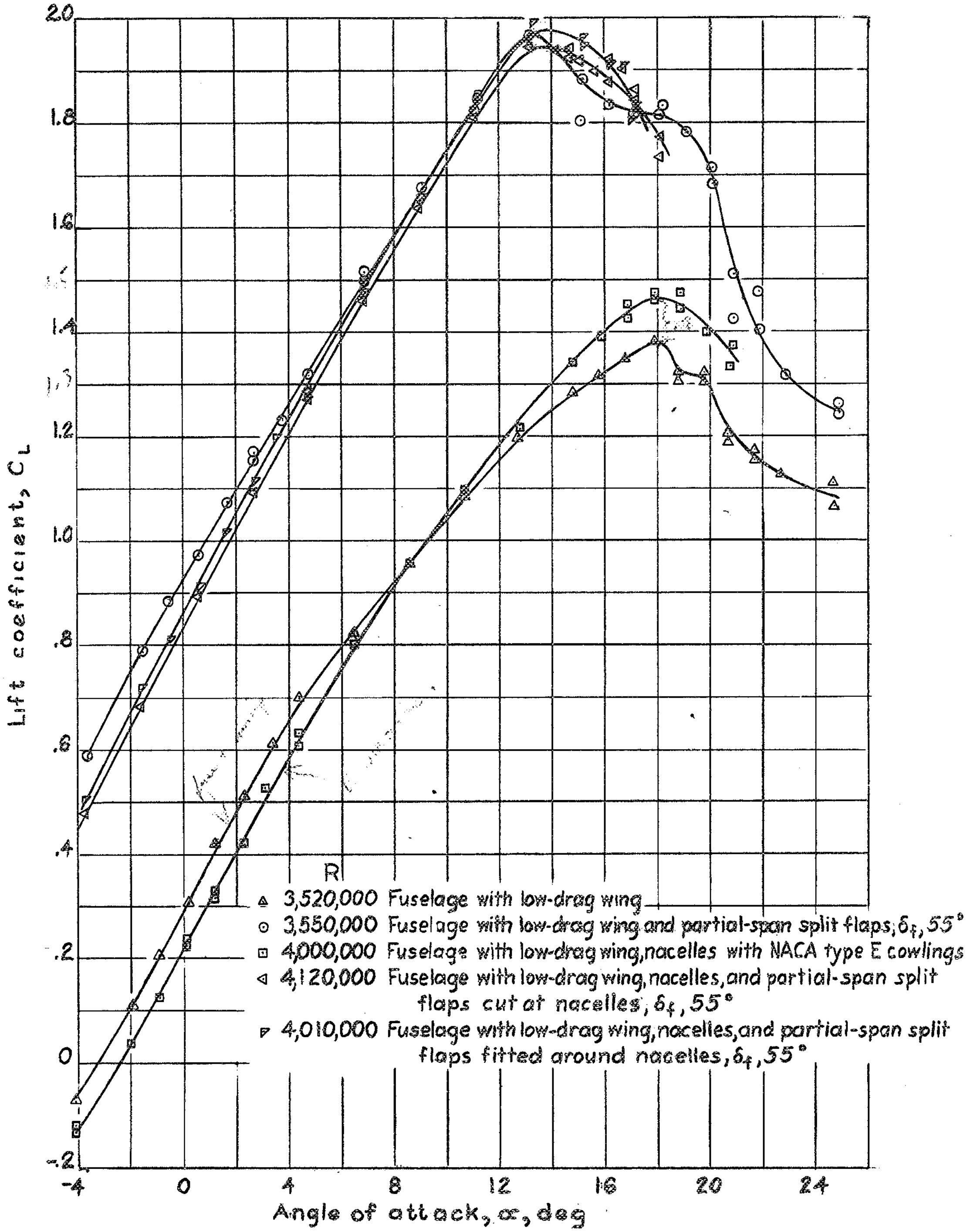


*Figure 9 - Variation of lift coefficient with angle of attack for model without nacelles and with two nacelles with NACA type E cowlings. q, 70 pounds per square foot.*

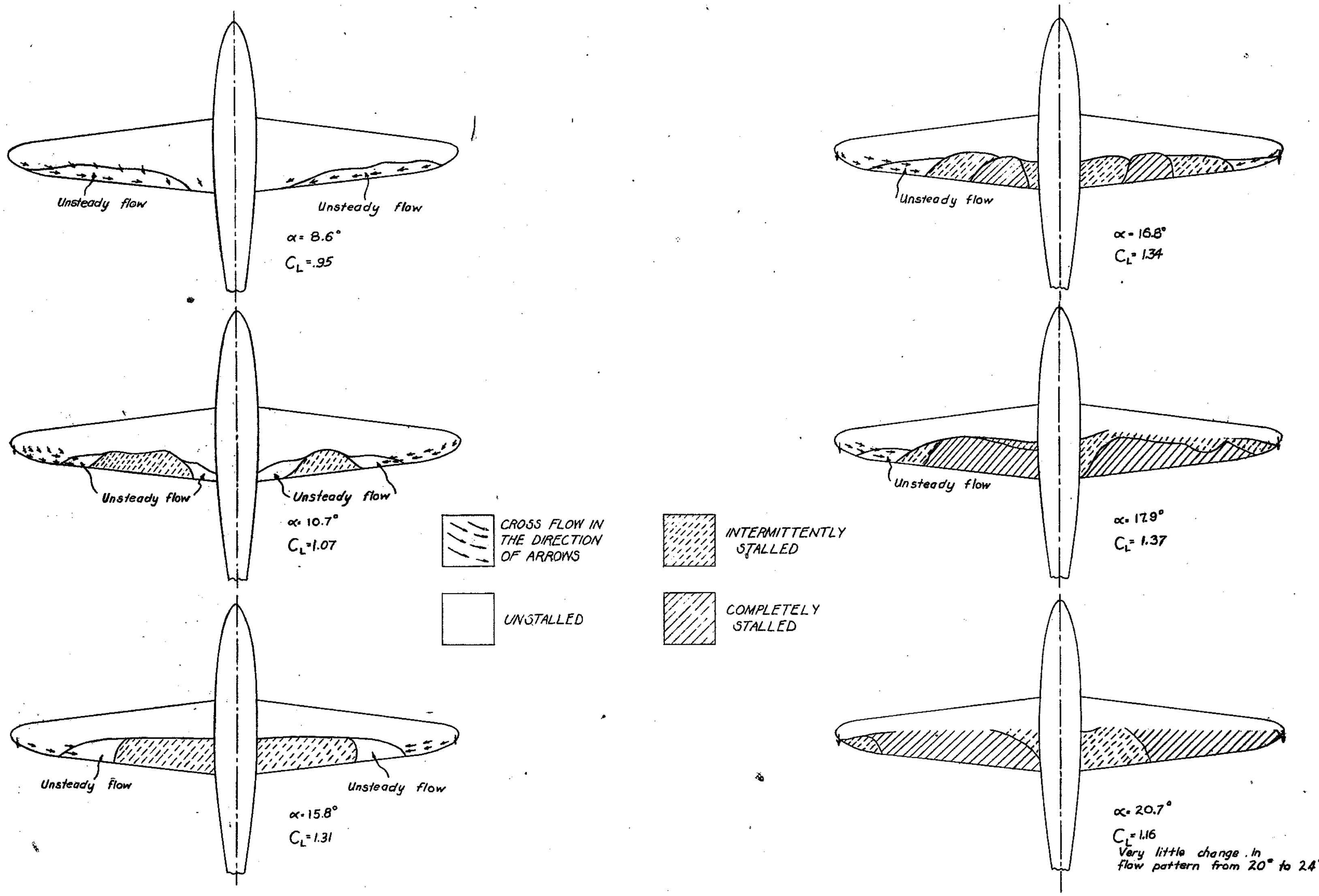


FIGURE 10.-STALL DIAGRAMS OF THE 1/6-SCALE SIMPLIFIED TWIN-ENGINE BOMBER MODEL WITHOUT NACELLES.
$q$, 70 POUNDS PER SQUARE FOOT; PRESSURE, 35 POUNDS PER SQUARE INCH ABSOLUTE; $\delta_f$, = 0°

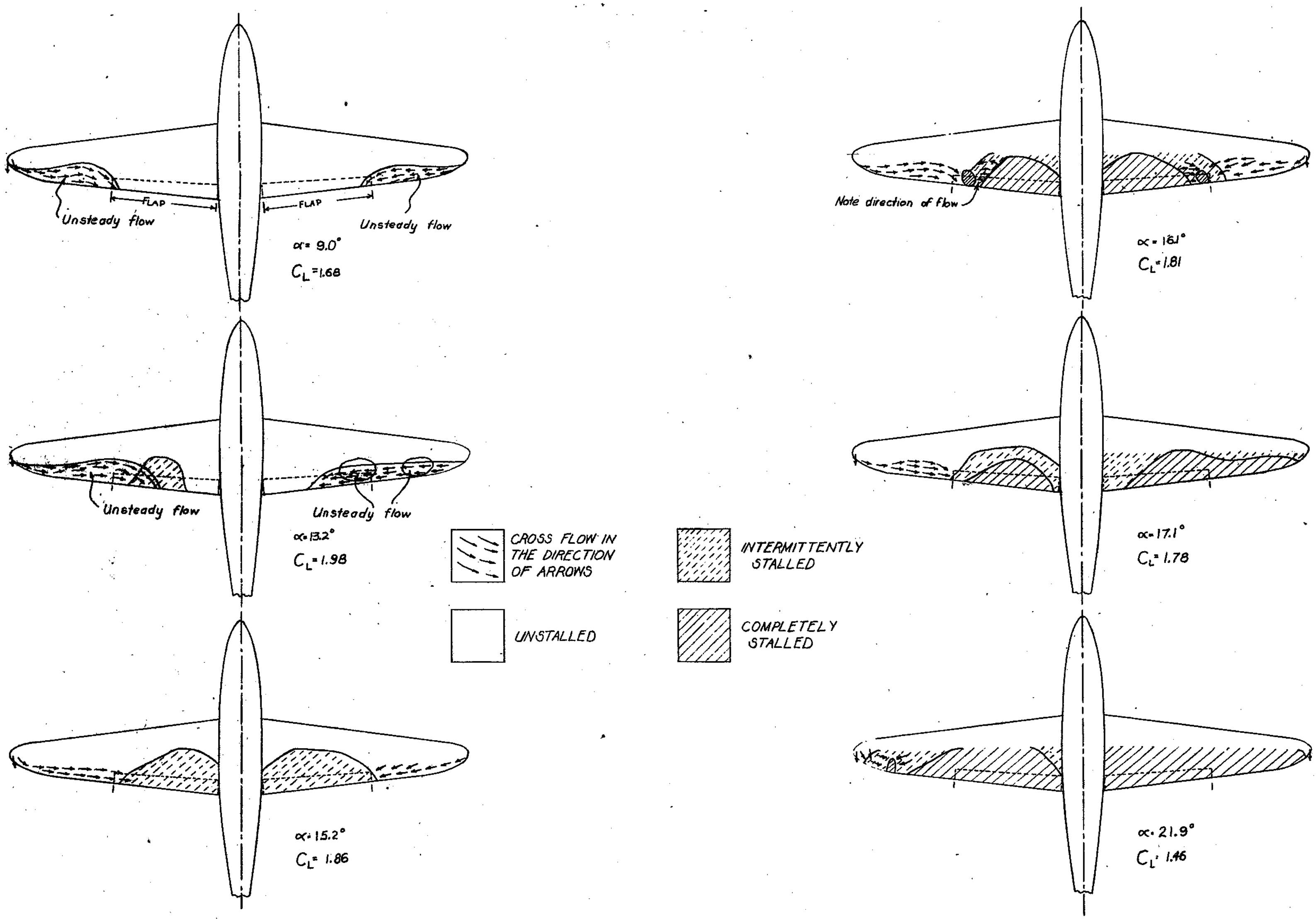


FIGURE 11.-STALL DIAGRAMS OF THE 1/6-SCALE SIMPLIFIED TWIN-ENGINE BOMBER MODEL WITHOUT NACELLES. q, 70 POUNDS PER SQUARE FOOT; PRESSURE, 35 POUNDS PER SQUARE INCH ABSOLUTE; $\delta_f$, = 55°.

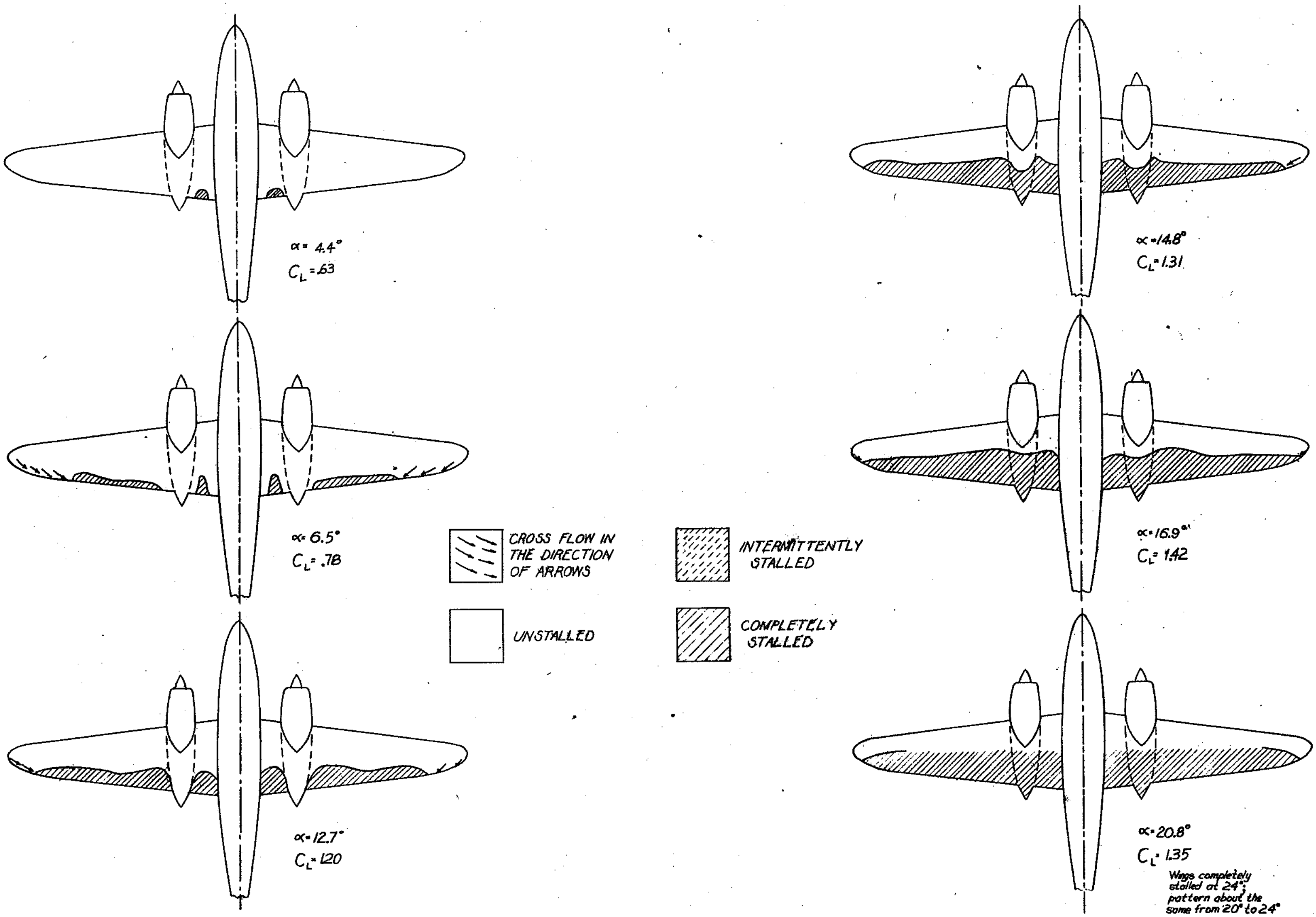


FIGURE 12.- STALL DIAGRAMS OF THE 1/6-SCALE SIMPLIFIED TWIN-ENGINE BOMBER MODEL WITH NACELLES WITH CONVENTIONAL COWLINGS.
q, 70 POUNDS PER SQUARE FOOT; PRESSURE, 35 POUNDS PER SQUARE INCH ABSOLUTE; $\delta_f = 0°$.

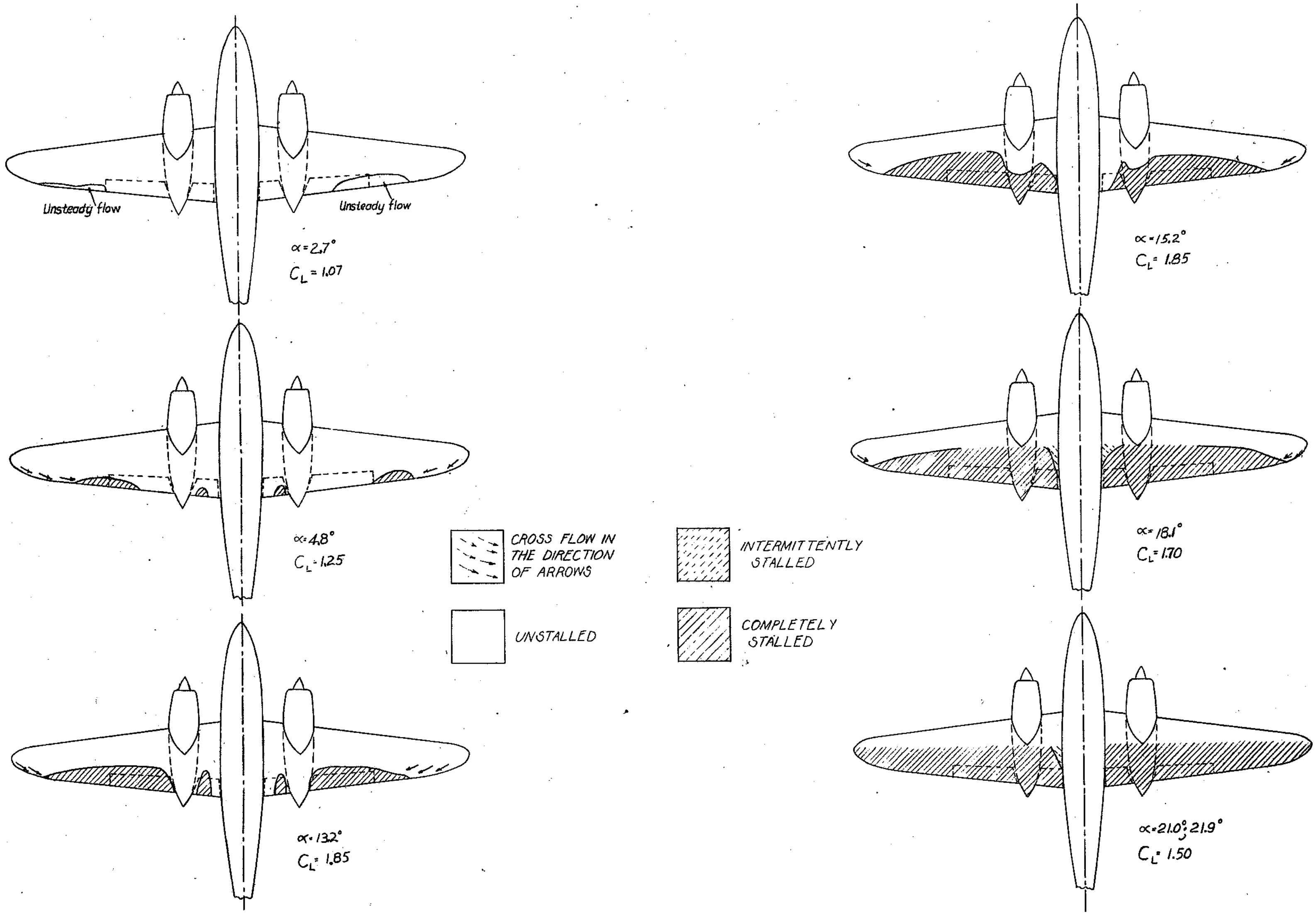


FIGURE 13.- STALL DIAGRAMS OF THE 1/6-SCALE SIMPLIFIED TWIN-ENGINE BOMBER MODEL WITH NACELLES WITH CONVENTIONAL COWLINGS. $q$, 70 POUNDS PER SQUARE FOOT; PRESSURE, 35 POUNDS PER SQUARE INCH ABSOLUTE; $\delta_f$, 55°. FLAPS CUT AT NACELLES.

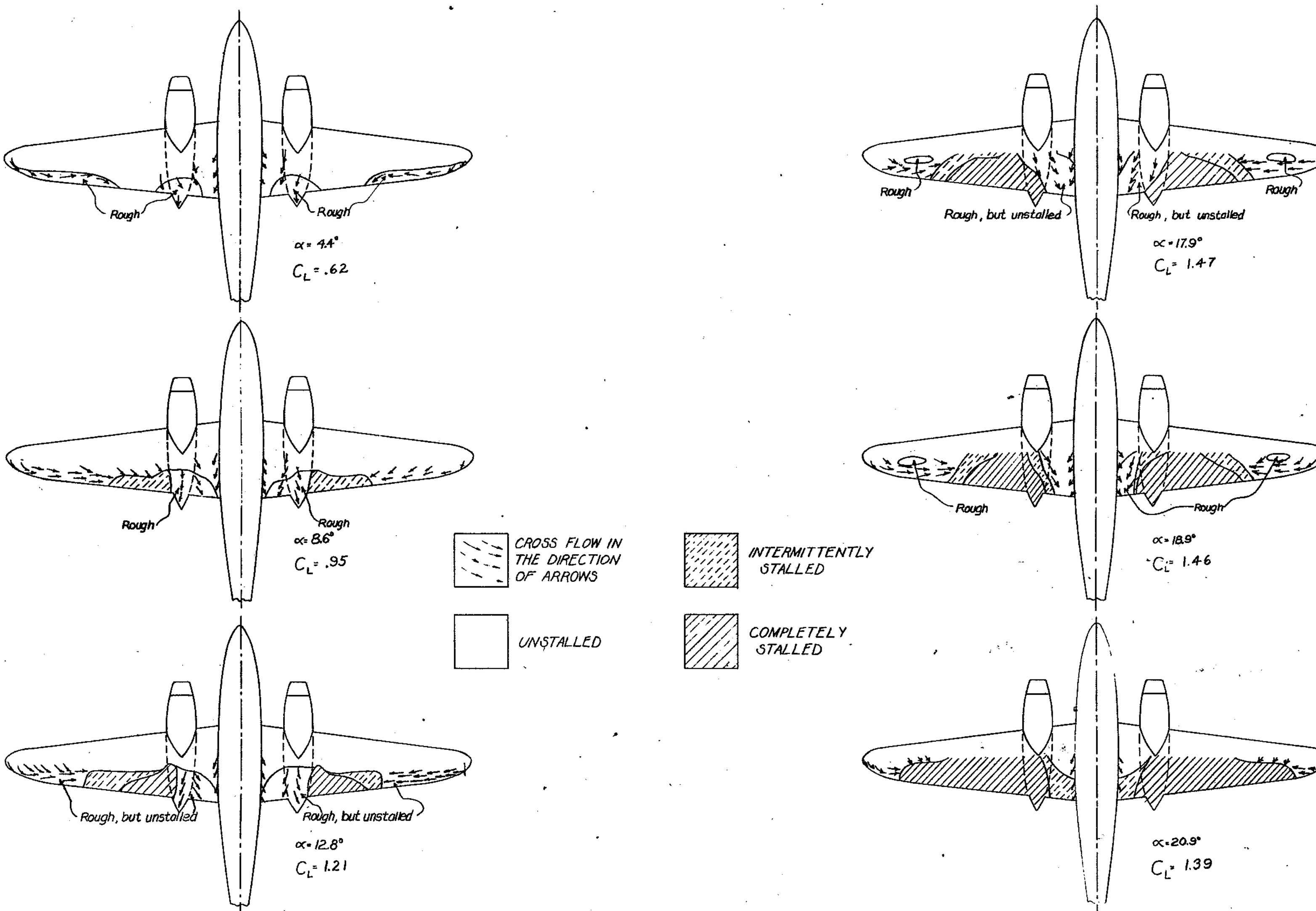


FIGURE 14.- STALL DIAGRAMS OF THE 1/6-SCALE SIMPLIFIED TWIN-ENGINE BOMBER MODEL WITH NACELLES WITH NACA TYPE E COWLINGS. $q$, 70 POUNDS PER SQUARE FOOT; PRESSURE, 35 POUNDS PER SQUARE INCH ABSOLUTE; $\delta_f$, 0°.

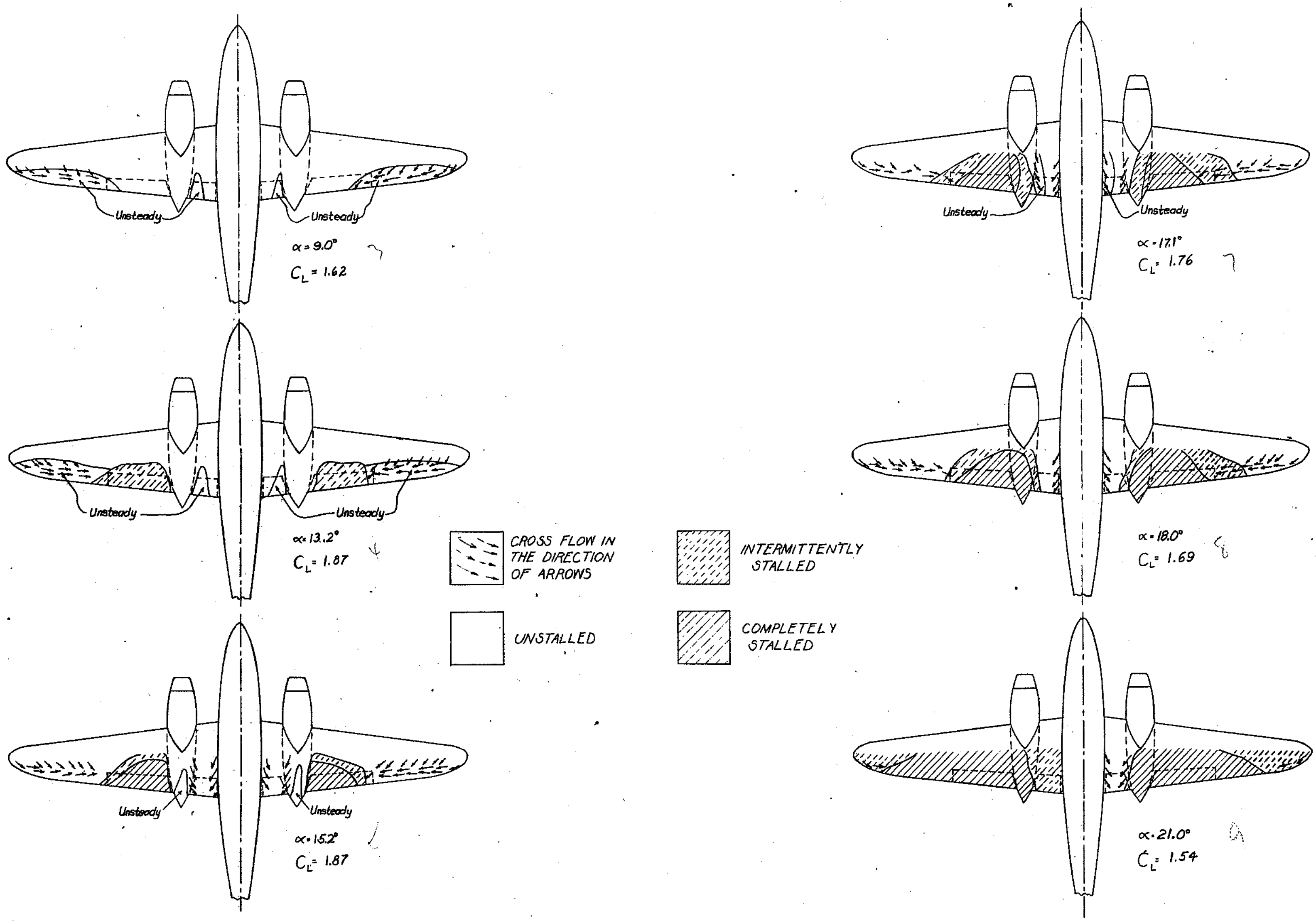


FIGURE 15.- STALL DIAGRAMS OF THE 1/6-SCALE SIMPLIFIED TWIN-ENGINE BOMBER MODEL WITH NACELLES WITH NACA TYPE E COWLINGS. $q$, 70 POUNDS PER SQUARE FOOT; PRESSURE, 35 POUNDS PER SQUARE INCH ABSOLUTE; $\delta_f$, 55°. FLAPS CUT AT NACELLES.

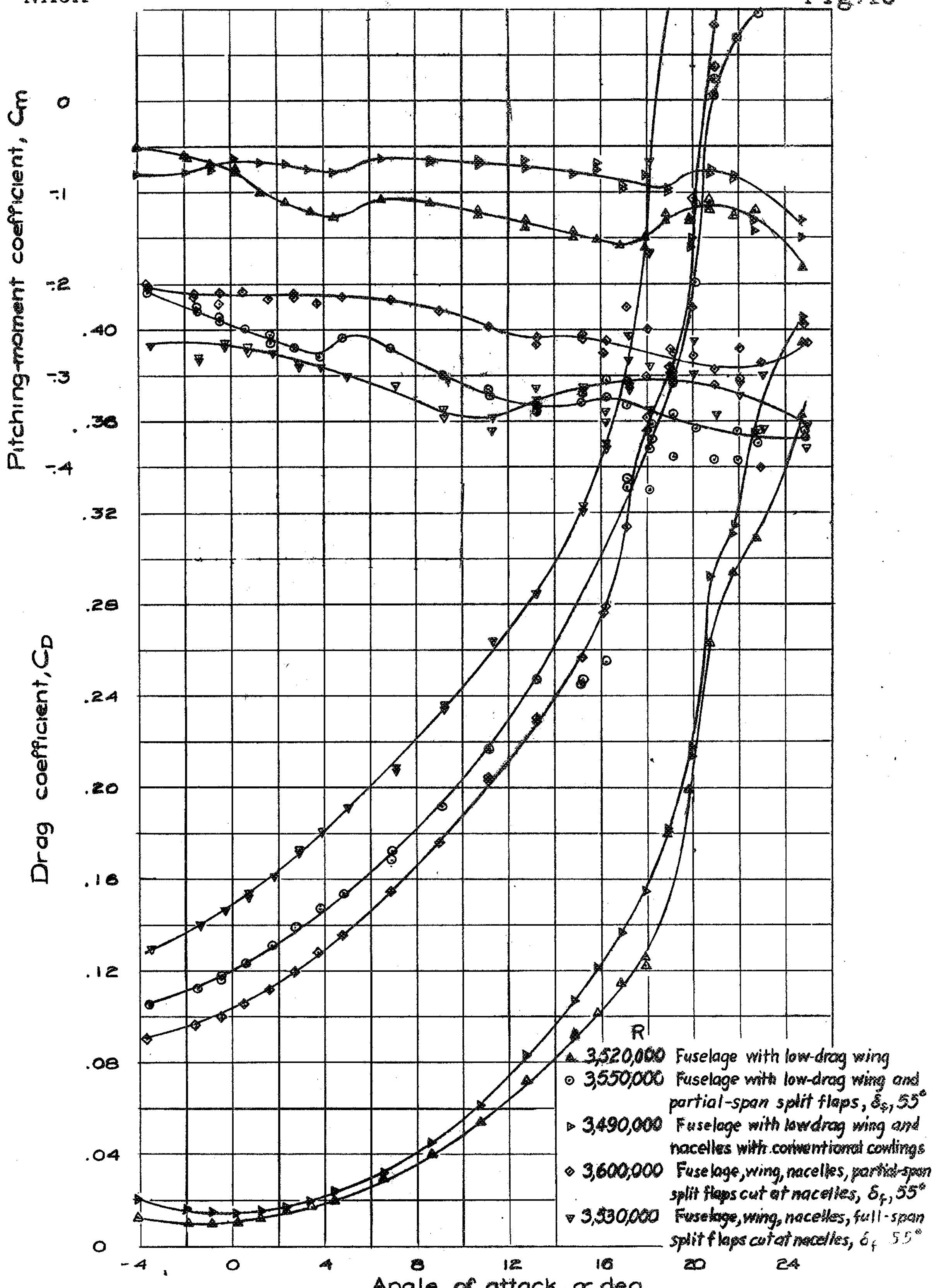


Figure 16.- Variation of drag and pitching-moment coefficients with angle of attack for model without nacelles and with two nacelles with conventional-type cowlings. q, 70 pounds per square foot.

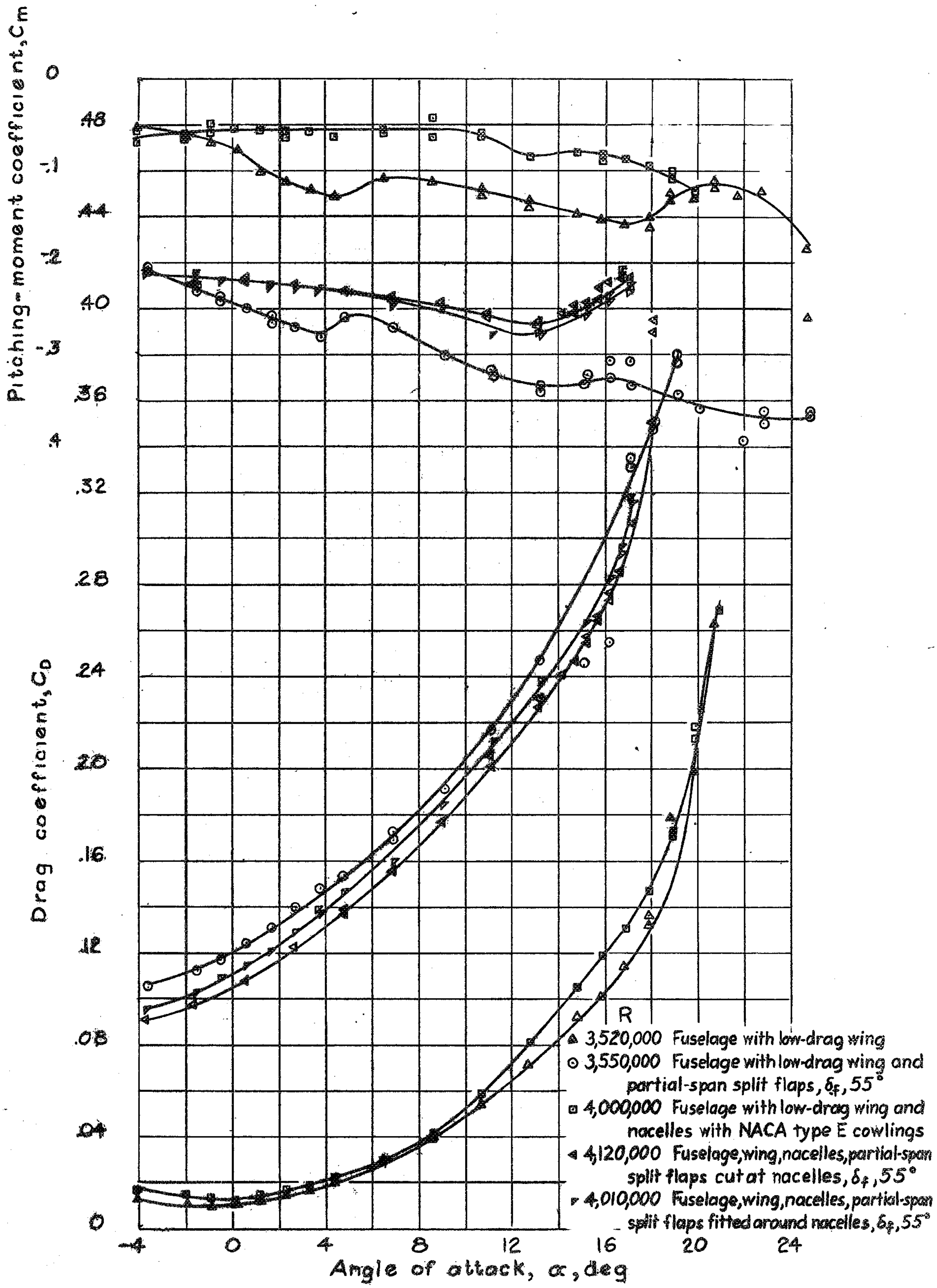


Figure 17.- Variation of drag and pitching-moment coefficients with angle of attack for model without nacelles and with two nacelles with NACA type E cowlings. q, 70 pounds per square foot.

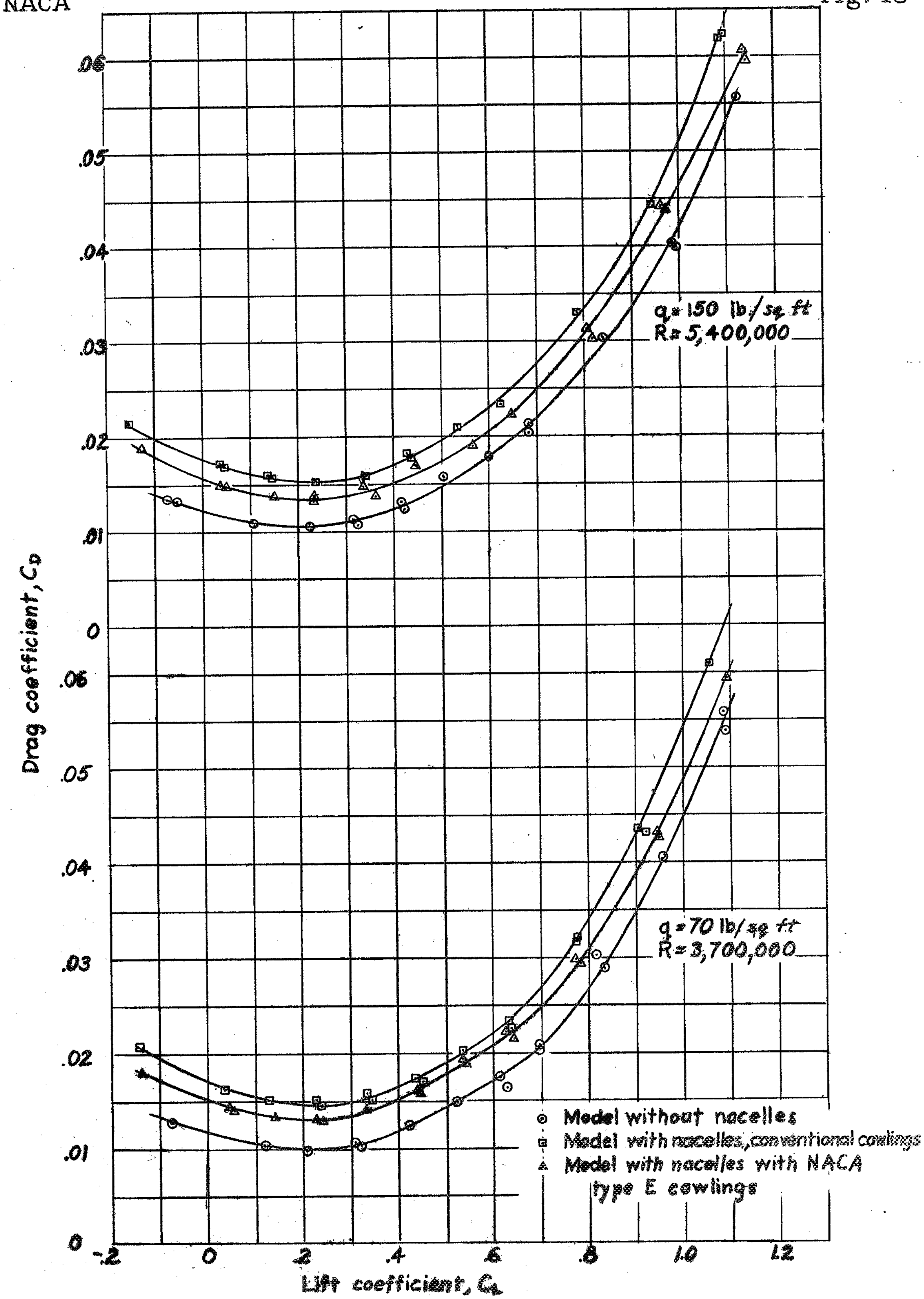


Figure 18.- Variation of drag coefficient with lift coefficient for model without nacelles and with two types of nacelle.

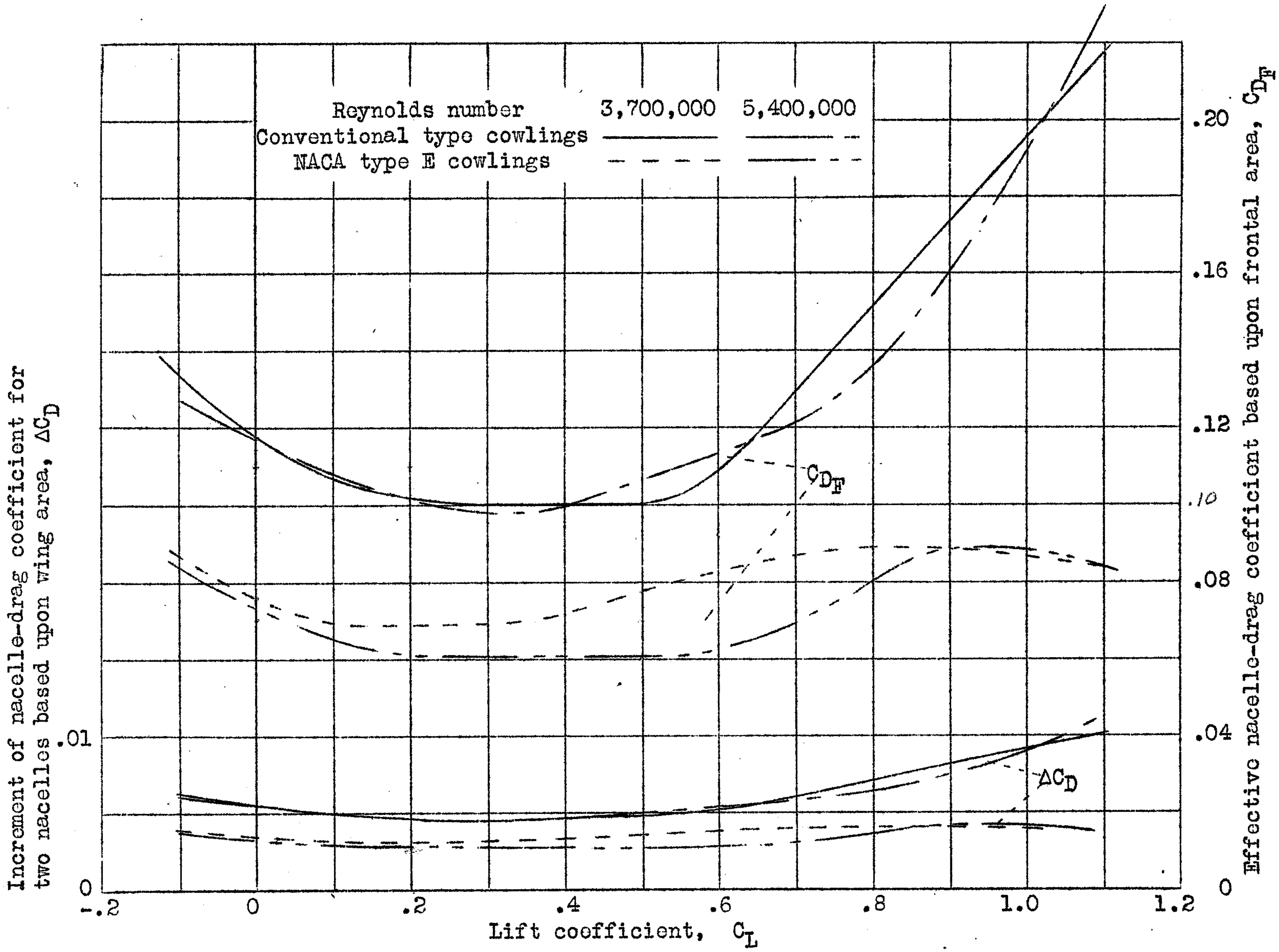


Figure 19.- Variation of nacelle-drag coefficients with lift coefficient.

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Fig. 19